

# Top Quark Physics at the Tevatron \*

Marc-André Pleier

Physikalisches Institut, Universität Bonn

Nussallee 12, 53115 Bonn, Germany

On behalf of the CDF and D0 Collaborations

## Abstract

The Tevatron proton-antiproton collider at Fermilab with its centre of mass energy of 1.96 TeV is currently the only source for the production of top quarks. Its increased luminosity and centre of mass energy in Run II allow both collider detectors CDF and D0 to study top quarks with unprecedented scrutiny.

Recent results on the top quark's pair production cross section and its properties such as mass, electric charge, helicity of the  $W$  boson in its decay and branching fraction  $B(t \rightarrow Wb)$  are presented and probe the validity of the Standard Model.

PACS numbers: 14.65.Ha, 12.38.Qk

## 1 Introduction

The existence of the top quark as the weak isospin partner of the bottom quark was already discussed in 1977 with the discovery of the bottom quark and hence a third quark generation. The self consistency of the Standard Model (SM) both required the existence of the top quark and allowed for increasingly precise predictions of properties like its mass from electroweak precision measurements. The top quark finally was discovered in 1995 by the CDF and D0 collaborations [1] in the mass range predicted by the SM, completing the SM quark sector. With a mass of  $170.9 \pm 1.8$  GeV [2], the top quark exhibits both the largest and the most precisely measured quark mass. It is the fermion coupling most strongly to the Higgs boson, and due to its extremely short lifetime of  $\approx 4 \cdot 10^{-25}$  s, it is the only quark that decays before it can hadronise, allowing the study of the decay of an essentially free quark.

Measuring the production cross section of the top quark and its different properties such as mass, electric charge,  $W$  boson helicity in its decay, branching fraction  $B(t \rightarrow Wb)$ , *etc.*, and comparing with predictions of the SM is a very powerful tool in searching for physics beyond the SM. The recently recorded large datasets at the Run II Tevatron allow for never-before-performed measurements of top quark properties like the electric charge, while other measurements like the top mass reach such a precision that they start to become limited by systematic uncertainties.

---

\*Presented at the “XXVII Physics in Collision” Symposium, Annecy, France, 26 - 29 June 2007.

This article focusses on the production of top quarks in pairs via the strong interaction using datasets with an integrated luminosity of up to  $1 \text{ fb}^{-1}$ . It also includes some measurements that became available shortly after the conference date. The production of single top quarks via the electroweak interaction with a first evidence observed by D0 is discussed in a different article in these proceedings [3]. A detailed description of the CDF and D0 detectors can be found in [4, 5].

## 2 Top Quark Pair Production and Decay

In  $p\bar{p}$  collisions at a centre of mass energy  $\sqrt{s} = 1.96 \text{ TeV}$ , top quarks are produced predominantly in pairs:  $p\bar{p} \rightarrow t\bar{t} + X$  via the strong interaction (85%  $q\bar{q}$  annihilation and 15% gluon-gluon fusion). At next-to-next-to-leading order, the corresponding SM cross section is  $6.77 \pm 0.42 \text{ pb}$  for a top quark mass of  $175 \text{ GeV}$  [6]. According to the SM, the top quark decays predominantly into  $W$  bosons and  $b$ -quarks. Hence, there are three event classes to be observed resulting from  $t\bar{t}$  decay, which depend on the decay mode of the  $W$  bosons:

(i) a so-called *dilepton* final state where both  $W$  bosons decay leptonically, resulting in two isolated high- $p_T$  leptons, missing transverse energy  $\cancel{E}_T$  corresponding to the two neutrinos and two jets, (ii) a *lepton+jets* final state where one  $W$  boson decays leptonically, the other one hadronically, resulting in one isolated high- $p_T$  lepton,  $\cancel{E}_T$  and four jets, and (iii) an *all-hadronic* final state where both  $W$  bosons decay to  $\bar{q}q'$  pairs, producing six jets. In all final states, two of the jets are  $b$ -jets (originating from the hadronisation of a  $b$ -quark). Additional jets can arise from initial and final state radiation.

The all-hadronic final state represents the biggest branching fraction of  $t\bar{t}$  events ( $\approx 46\%$ ), but it is also difficult to separate from the large multijet background. The dilepton final state not counting  $\tau$  leptons constitutes  $\approx 5\%$  of the  $t\bar{t}$  events and gives the cleanest signal but suffers from low statistics. The lepton+jets events in the  $e$ +jets or  $\mu$ +jets channels yield  $\approx 29\%$  of the branching fraction and provide the best compromise between sample purity and statistics.

## 3 Top Quark Pair Production Cross Section Measurements

Measurements of the top quark pair production cross section provide an important test of the predictions from perturbative QCD calculations at high transverse momenta. Analysing different decay channels helps to improve statistics of top events and studies of properties, as well as the probing of physics beyond the SM that might result in enhancement/depletion in some particular channel via novel production mechanisms or decay modes. Instead of quoting single cross section results in the following subsections, all current measurements are summarised in Figure 1.

Due to the selection of datasets enriched in top quark pairs and the necessity of understanding object identification, background modelling and sample composition, cross section measurements form the foundation for all further property analyses like the ones described in the subsequent sections of this article.

### 3.1 Dilepton Final State

Dilepton events are usually selected by requiring two isolated high  $p_T$  leptons,  $\cancel{E}_T$  and at least two central energetic jets in an event. The main physics backgrounds exhibiting both real leptons and  $\cancel{E}_T$  arise from  $Z/\gamma^*$ +jets production with  $Z/\gamma^* \rightarrow \tau^+\tau^-$ ,  $\tau \rightarrow e, \mu$  and the production of dibosons ( $WW, ZZ, WZ$ ). Instrumental backgrounds mainly arise from misreconstructed  $\cancel{E}_T$  due to resolution effects in  $Z/\gamma^*$ +jets production with  $Z/\gamma^* \rightarrow e^+e^-/\mu^+\mu^-$ , but also from  $W$ +jets and QCD multijet production where one or more jets fake the isolated lepton signature. While the physics backgrounds are estimated from Monte Carlo, the instrumental backgrounds are usually modelled using data.

The selected data samples can be further enriched in signal by requiring additional kinematical event properties like the scalar sum of the jet  $p_T$ s  $H_T$  to be above a certain threshold or discarding events where both leptons have the same electric charge. The purities in these samples are usually quite good with a signal to background ratio (S/B) better than 2 at least, but the statistics are low. To enhance the acceptance for dilepton final states and especially include “1 prong” hadronic  $\tau$  decays, the selection can be loosened to require only one fully reconstructed isolated lepton ( $e, \mu$ ) in addition to an isolated track (“ $\ell$ +track analysis”).

A first measurement of the lepton+tau final state was recently performed by D0, using events with hadronically decaying isolated taus and one isolated high  $p_T$  electron or muon. In this case, the sample purity was enhanced by requiring  $b$ -jet identification in the event. The result is shown together with other measurements in Figure 1.

### 3.2 Lepton+Jets Final State

Lepton+jets events typically are selected by requiring one isolated high  $p_T$  lepton ( $e, \mu$ ),  $\cancel{E}_T$  and at least 4 jets. The main physics background here comes from  $W$ +jets production while the main instrumental background arises from QCD multijet production where a jet fakes the isolated lepton signature. Accordingly selected samples exhibit a S/B around 1/2. It is possible to extract the cross section using either purely topological and kinematic event properties combined in a multivariate discriminant to separate the  $t\bar{t}$  signal from background, or by adding identification of  $b$ -jets. An advantage of topological analyses is that they do not depend on the assumption of 100% branching of  $t \rightarrow Wb$  and are therefore less model-dependent than tagging analyses. Requiring  $b$ -jet identification, however, is a very powerful tool to further suppress the backgrounds which typically exhibit little heavy flavour content, allowing for signal extraction in lower jet multiplicities and providing very pure signal samples: a S/B > 10 can easily be achieved in selections requiring at least four jets if two identified  $b$ -jets are required.

$b$ -jets can be identified based on the long *lifetime* of  $B$  hadrons resulting in significantly displaced secondary vertices with respect to the primary event vertex or large significant impact parameters of the corresponding tracks. Combining this type of information into a neural network tagging algorithm,  $b$ -tagging efficiencies of about 54% are achieved while only about 1% of light quark jets are misidentified as  $b$ -jets, resulting in an improved S/B in tagged analyses. A second way to identify  $b$ -jets is to reconstruct *soft leptons* inside a jet that come from semileptonic  $B$  decays – so far only soft- $\mu$  tagging has been deployed in  $t\bar{t}$  analyses.

Using lifetime  $b$ -tagging, D0 was also able to perform a first  $\tau$ +jets cross section analysis, using events with hadronically decaying isolated taus – the result is shown together with other measurements in Figure 1.

### 3.3 All-Hadronic Final State

To study the all-hadronic final state, events with at least six central energetic jets and no isolated high  $p_T$  leptons are selected. Since QCD multijet production represents a background which is orders of magnitude larger than the signal process,  $b$ -jet identification is mandatory for this final state. To allow further separation of signal and background, multivariate discriminants based on topological and kinematic event properties are deployed.

### 3.4 Summary

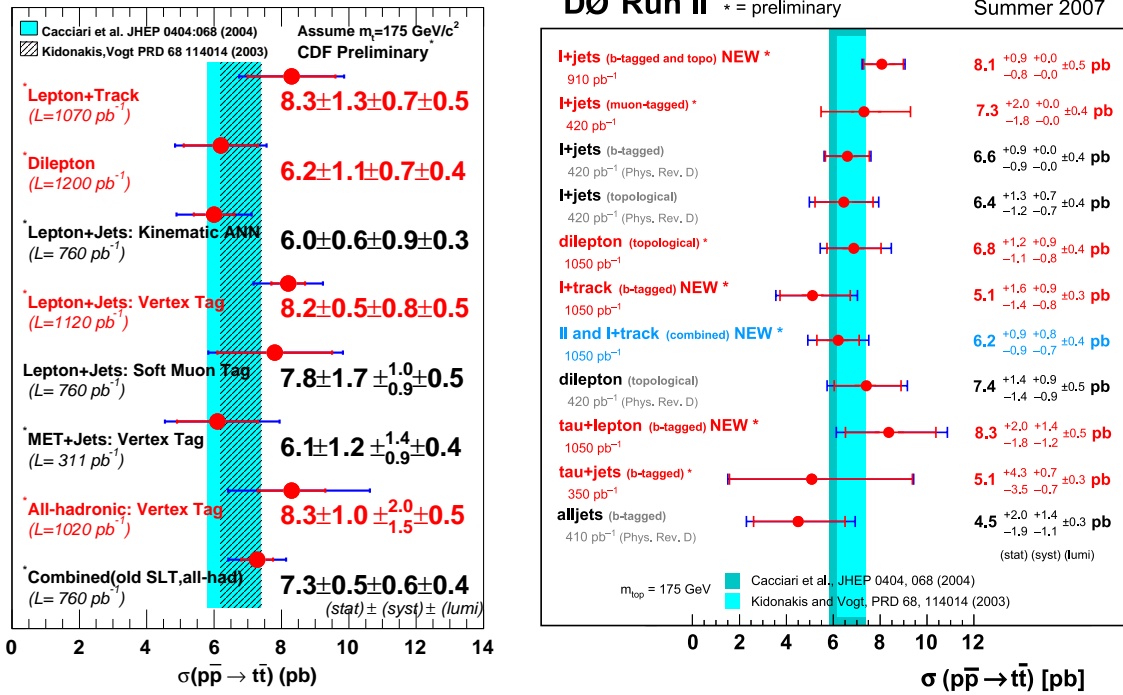


Figure 1: Top quark pair production cross-section measurements by CDF (left) and D0 (right) in comparison with theory predictions shown as coloured bands. If a systematic uncertainty is shown as 0, it is included in the statistical uncertainty.

Figure 1 shows an overview of recent cross section measurements performed by CDF and D0. All measurements are in good agreement with the SM prediction and with each other – the single best measurements reaching a relative precision of  $\Delta\sigma/\sigma=12\%$ . With increasing datasets, these measurements naturally start to become limited by systematic uncertainties which in return can be further constrained using additional data. For an integrated luminosity of  $2 \text{ fb}^{-1}$ , a relative precision of  $\Delta\sigma/\sigma=10\%$  should be achievable, providing stringent tests to theory predictions.

## 4 Measurement of $B(t \rightarrow Wb) / B(t \rightarrow Wq)$

The ratio of branching fractions  $R = B(t \rightarrow Wb) / \sum_{q=d,s,b} B(t \rightarrow Wq)$  is constrained within the SM to  $0.9980 < R < 0.9984$  at 90% CL [7], assuming three fermion generations, unitarity of the CKM matrix and neglect of non- $W$  boson decays of the top quark. The most precise measurement to date has been performed by D0 in the lepton+jets channel using data corresponding to an integrated luminosity of  $900 \text{ pb}^{-1}$  by comparing the event yields with 0, 1 and 2 or more  $b$ -tagged jets. This measurement obtains the following result for  $R$  from a simultaneous fit of  $R$  and the  $t\bar{t}$  cross section (which is also shown in Figure 1):  $R = 0.991^{+0.094}_{-0.085}$  (stat + syst). This result is in agreement with the SM expectation.

## 5 Measurement of the Top Quark Electric Charge

The electric charge of the top quark can be inferred from the electric charges of its decay products. However, there is an inherent ambiguity when pairing  $W$  bosons and  $b$ -jets in a top quark pair event resulting in possible charges of  $|Q| = 2e/3$  or  $4e/3$ , the latter being predicted in exotic models [8]. D0 has published a first measurement of the electric charge of the top quark excluding the hypothesis of only exotic quarks of charge  $|Q| = 4e/3$  being produced at 92% CL by analysing lepton+jets events with two identified  $b$ -jets, obtaining the  $W$  boson charge from the lepton charge, the  $b$ -jet charge from a track-based jet charge algorithm and assigning the  $W$  boson –  $b$ -jet pairing based on a kinematic event fit [9]. Similarly, CDF obtained a preliminary result on the top quark charge using lepton+jets and dilepton events with an observed  $2\ln(\text{Bayes Factor})$  of 12.01, meaning that the data favour very strongly the SM top quark hypothesis over the exotic model.

## 6 Measurement of the $W$ Boson Helicity in $t\bar{t}$ Decays

Top quark decay in the  $V-A$  charged current weak interaction proceeds only via a left-handed ( $f^- = 30\%$ ) and a longitudinal ( $f^0 = 70\%$ ) fraction of  $W$  boson helicities, which is reflected in the angular distribution of the charged lepton relative to the line of flight of the top quark in the  $W$  boson rest frame in lepton+jets final states. Any observed right-handed fraction  $f^+ > \mathcal{O}(10^{-4})$  would indicate physics beyond the SM.

The most precise measurement to date has been performed by CDF using a dataset corresponding to an integrated luminosity of  $1.7 \text{ fb}^{-1}$  and comparing the above mentioned angular distribution in data to templates for longitudinal, right- and left-handed signal plus a background template. When fitting both  $f^0$  and  $f^+$  simultaneously, the result is  $f^0 = 0.61 \pm 0.20$  (stat)  $\pm 0.03$  (syst),  $f^+ = -0.02 \pm 0.08$  (stat)  $\pm 0.03$  (syst); constraining  $f^0$  respectively  $f^+$  to their SM values when fitting  $f^+$  respectively  $f^0$ , the result is  $f^0 = 0.57 \pm 0.11$  (stat)  $\pm 0.04$  (syst),  $f^+ = -0.04 \pm 0.04$  (stat)  $\pm 0.03$  (syst),  $f^+ < 0.07$  (95% CL), in agreement with expectations from the SM.

## 7 Measurement of the Top Quark Mass

The top quark mass is a fundamental SM parameter that is not predicted by the SM theory itself. It can be used in conjunction with the  $W$  boson mass to constrain the mass of the still undiscovered Higgs boson via radiative corrections.

One of the most crucial ingredients for top quark mass measurements is the jet energy scale (JES), relating the measured jet energy to the parton energy. Top events can provide an additional in situ calibration source via hadronic  $W$  boson decays by using the well-known mass of the  $W$  boson as a constraint. Additional future constraints on the  $b$ -JES could be derived from the study of  $Z \rightarrow b\bar{b}$  decays.

The most precise measurements of the top quark mass are achieved in the lepton+jets final state due to the high branching fraction and yet good S/B, the hadronic  $W$  boson decay allowing for additional JES calibration and the overconstrained event kinematics as only one neutrino is present in the final state.

The top quark mass has been measured in all decay modes using different analysis methods that can be roughly separated in two categories: *Template methods* compare distributions of observables sensitive to the top quark mass in data with template distributions for varying top quark masses. *Dynamical methods* try to maximise the use of information in each candidate event by calculating a per-event probability density as a function of the top quark mass, usually based on leading order matrix elements.

An example for a dynamical method is the “Matrix Element Method” pioneered by D0 in the lepton+jets channel during Run I which yielded the most precise single measurement of that time [10]. It also gives the most precise measurements obtained thus far in Run II for both CDF and D0 in the lepton+jets channel. Using the measured fraction of signal events, in these measurements the per-event probability is obtained as a linear combination of the signal and background probabilities. These are evaluated based on leading order matrix elements for the  $t\bar{t}$  signal and  $W$ +jets main background, also folding in the detector resolution and summing over the different possible jet-parton assignments, solutions for the longitudinal neutrino momentum and possibly  $b$ -tagging event probabilities.

Fig. 2 shows the results of these measurements together with all other measurements considered for the current world average mass of  $170.9 \pm 1.8$  GeV [2]. By the end of Run II, a final top quark mass uncertainty of  $\Delta m_t = 1$  GeV should be achievable, which will – together with an improved measurement of the  $W$  boson mass – provide stringent constraints on the mass of the Higgs boson. Following from the current world average top quark mass, the most likely Higgs boson mass is  $m_H = 76^{+33}_{-24}$  GeV respectively  $m_H < 144$  GeV at 95% CL, promising an interesting competition between Tevatron and LHC for the first evidence of the Higgs boson.

## 8 Summary

A wealth of top analyses is being pursued at the Tevatron, which continue to probe the validity of the SM. While some measurements are reaching the precision of the theory predictions and thus provide stringent tests thereof, others are still statistically limited, leaving room for physics beyond the SM. So far, all measurements are in agreement with the SM.

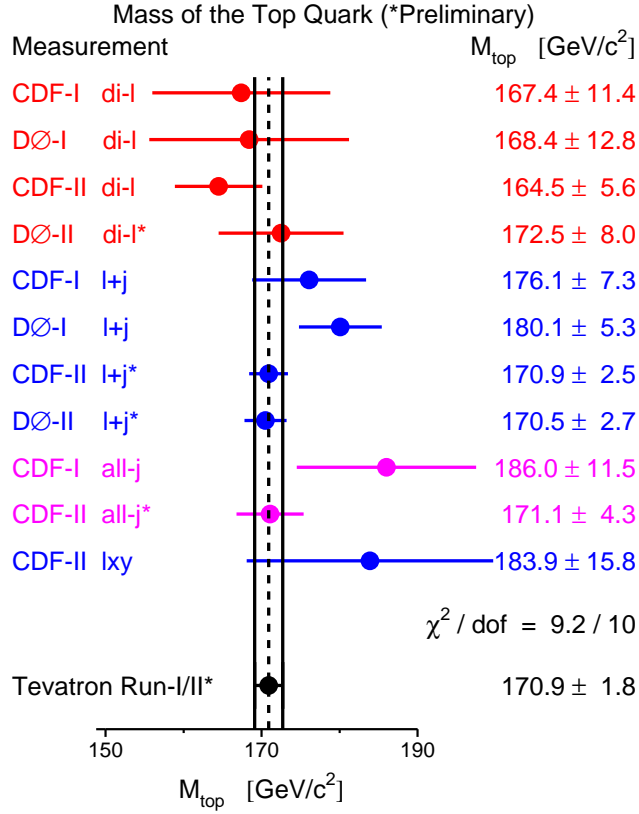


Figure 2:  $m_t$  measurements used as an input for the current preliminary world average.

More detailed descriptions of the analyses presented here can be found online [11]. Continuously improving the analysis methods, and using the increasing integrated luminosity from a smoothly running Tevatron, expected to deliver more than  $6 \text{ fb}^{-1}$  by the end of Run II, we are moving towards precision measurements and hopefully discoveries within and outside the SM.

## Acknowledgements

The author would like to thank the organisers for a rich and rewarding conference and to acknowledge the generous support of the Alexander von Humboldt Foundation.

## References

- [1] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995);  
DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **74**, 2632 (1995).
- [2] Tevatron Electroweak Working Group, hep-ex/0703034 (2007).
- [3] C. Ciobanu, for the CDF and DØ collaborations, “Single-Top-Quark Physics at Hadron Colliders”, these proceedings.

- [4] CDF Collaboration, R. Blair *et al.*, Fermilab-Pub-96-390-E (1996).
- [5] D0 Collaboration, V. M. Abazov *et al.*, Nucl. Instr. Meth. A **565**, 463 (2006).
- [6] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
- [7] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
- [8] D. Chang *et al.*, Phys. Rev. D **59**, 091503 (1999); **61**, 037301 (2000);  
D. Choudhury *et al.*, Phys. Rev. D **65**, 053002 (2002).
- [9] D0 Collaboration, V. M. Abazov *et al.*, Phys. Rev. Lett. **98**, 041801 (2007).
- [10] D0 Collaboration, V. M. Abazov *et al.*, Nature **429**, 638 (2004).
- [11] <http://www-d0.fnal.gov/Run2Physics/top/index.html>;  
<http://www-cdf.fnal.gov/physics/new/top/top.html>